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TANKAGE FAILURES OF AEROBEE - HI AND VANGUARD ROCKETS.(U)

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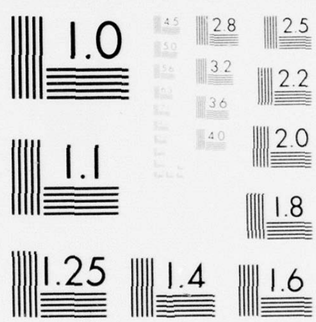

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TANKAGE FAILURES OF AEROBEE-HI AND VANGUARD ROCKETS

J. E. Srawley

METALLURGY DIVISION

December 1956

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MEMO REPORT NO. 656

TANKAGE FAILURES OF AEROBEE - HI AND VANGUARD ROCKETS

BY

J. E. SRAWLEY

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ABSTRACT

The failures of two type 410 stainless steel tankage components of NRL Aerobee - Hi rockets at Fort Churchill, Manitoba, have been investigated. One failure is considered to have originated at a section of hand repair to a longitudinal seam weld of the oxidizer (nitric acid) tank. The other failure originated by stress corrosion cracking of the end of the helium pressurizing tank, which is in contact with the nitric acid while stressed almost to its yield strength. The two failures are important, not only in relation to other Aerobee - Hi rockets, but also in relation to Vanguard rockets, which are constructed of the same material and also use nitric acid. Three failures of Vanguard tankages, which occurred during testing at the manufacturer's plant, are also discussed. These were test items only, and not intended for launching. In each case the reasons for failure are understood and appropriate remedial action has been taken.

A program of stress corrosion testing is being carried out by the manufacturer of the rockets and present indications are that the use of 1/2 to 3/4% anhydrous HF as an inhibitor in the acid will reduce the possibility of stress corrosion failure very significantly. The effect of this on rocket performance is being checked and it seems likely that it will be tolerable.

Improvements in welding procedures and inspection are recommended and are being effected by the manufacturer. Additionally, a reduction in operating pressure of the Aerobee - Hi helium tank was agreed upon between representatives of the manufacturer and of the U. S. Naval Research Laboratory at the launching site.

PROBLEM STATUS

This is a final report on the metallurgical investigation of the failures.

AUTHORIZATION

NRL (Atmosphere and Astrophysics) 71A02-89 UNCLASSIFIED

TANKAGE FAILURES OF AEROBEE - HI AND VANGUARD ROCKETS

Introduction

The recent consecutive failures of the tankage systems of the first two Aerobee - Hi rockets intended to be launched from the Fort Churchill, Manitoba, site have aroused concern regarding not only the Aerobee - Hi rocket, but also the Vanguard second stage rocket, which has some features of the tankage system in common with the Aerobee - Hi. Careful examinations of the two Aerobee - Hi failures have been made and the purpose of this report is to provide an account of these investigations, of what is known of three proof test failures of Vanguard tankages, and of remedial action either already started or recommended.

The Aerobee - Hi and the Vanguard are manufactured by the same Company (herein referred to as the A. Co). The tankages of both are constructed principally of thin, type 410 stainless steel sheet, assembled by Argon gas shielded tungsten arc welding and heat treated, as an assembly, to a hardness of Rockwell C 39-45. Different heat treatment schedules are specified for the two rockets but both are heat-treated by the same sub-contractor and the same controlled atmosphere furnace is used for the Aerobee - Hi and Vanguard rockets. This fact is not merely incidental, heat treatment facilities of this size and capability are available in only a few localities. It is understood that no other is available in the Los Angeles region.

The tankage systems of the two rockets are generally similar. In each case there is a tank for fuel, a tank for the oxidizing agent (nitric acid) and a pressure tank containing helium to pressurize the fuel and oxidizer tanks when the rocket is fired. The two systems differ in their detailed arrangements which will be described later. In order to reduce weight as much as possible, the sections of the tanks are only sufficient to support the maximum anticipated loads with a margin of safety of 10%. That is to say, the minimum permissible 0.2% offset yield strength of the material is 110% of the major stress that is anticipated. Details of calculated nominal stresses will be given later, however, in considering the failures it is well to bear this general rule in mind.

With this general background the Aerobee - Hi failures will first be considered, followed by a discussion of the Vanguard in relation to them.

Construction, Manufacture and Testing of the Aerobee - Hi Tankage

A schematic drawing of the Aerobee - Hi, showing the locations of some of the welded joints, is shown in Figure 1. Details of the weld joints G2 and G3 are shown in Figure 2. The brief description given in the manufacturer's specification AES-A2821.6a reads as follows:

"The tank assembly is a cylindrical chamber nominally 15 inch diameter by 162.5 inches long*. It is separated into three sections. The forward or pressure tank section stores high pressure gas and is made up of hemispherical heads. The aft hemispherical head also serves as the forward end of the oxidizer tank. The aft end of the oxidizer tank is capped with a double radius head which in turn serves as the forward end of the fuel tank. The aft end of the fuel tank is capped by a double radius head. The principal material of construction is Type 410 corrosion-resistant steel".

Some detail information concerning the tankage is given in the manufacturer's "Outline of Navy Aerobee - Hi 410 Tank Assembly" which is reproduced as Appendix I of this report. This includes information on design, material assembly, welding, heat treatment and pressure testing.

Design calculations of stresses were made on the basis of the minimum thicknesses of the various sections allowed by the specified dimensions and tolerances. For convenient reference the following pressures and corresponding major stresses are listed below:

Pressures and Stresses in Aerobee - Hi

	Helium Tank		Propellant Tanks	
	Pressure psig	Stress psi	Pressure psig	Stress psi
Minimum Yield		142,000		142,000
Proof Test	4000	142,000	550	129,000
Rupture (Calc.)	4900	175,000	750	175,000
Operating	3750	132,000	450	105,000
Reduced Operating	3400	120,000	450	105,000

The last item, reduced operating pressure for the helium tank, was established at Fort Churchill following the failure of NRL #45.

Failure of Aerobee - Hi NRL #48 Oxidizer Tank during Hydrostatic Proof Test at Fort Churchill

This failure occurred at the launching site at Fort Churchill during proof testing prior to preparation of the rocket for firing. The rocket had been proof tested by A. Co. prior to shipment as outlined in Appendix I.

* In Figure 1 a skirt which is riveted to the forward end is omitted, thus reducing the overall length shown in that Figure to 155 in.

At Fort Churchill pressure was applied to the oxidizer tank hydrostatically while the rocket was resting horizontally in a suitable fixture. At approximately 520 psig pressure, corresponding to a calculated maximum principal tensile stress of 121,000 psig, the tank burst longitudinally along weld #L4. Figure 3 is a view of the whole rocket from the forward end showing the location of the failure. Figure 4 shows the burst section in more detail, while Figure 5 is a close up of the central section of the fracture.

Diagnosis of the failure depends upon careful consideration of the fracture. The fracture surfaces are of the oblique shear type along their entire lengths. At various points the fracture plane changes abruptly to the alternate conjugate shear plane. Near the center, fracture is located at the junction of the weld and the parent-metal, approximately one-half of it being on one side of the weld and the other half on the other side of the weld. Near the center, therefore, the fracture passes through the weld from one side to the other. Toward the two ends the fracture leaves the weld and, at each end, terminates by circumferential tearing. These features can all be distinguished in Figures 4 and 5. In the region where the fracture crosses the weld (Figure 5) a small piece of the weld can be seen to be almost detached from the remainder of the weld bead on the lower fractured surface. The only apparent explanation for the position of this piece is that separation through the weld must have occurred at a time when two longitudinal splits already existed, on the lower side of the weld forward of the piece and on the upper side of the weld aft of it. It also appears that the longitudinal split on the aft side must have initiated before the one on the forward side, since it completed its run through the weld before the second split had time to do so. As soon as the two splits were joined by the end of the upper one running through the weld into the lower one, there would be no force acting to cause the lower split to continue to run in the aft direction.

It is surmized that fracture first initiated somewhat aft of the place where it crosses the weld and, while propagating aft without interference, was somehow hindered in its forward propagation. The resultant stresses caused initiation of the second fracture somewhat forward of the crossing point and below the weld. As the fractured surfaces continued to move apart, the inner ends of both fractures were deflected into the weld so that the small central piece was rotated until the upper fracture finally ran through the weld and joined the lower one.

Examination of the fractured pieces shows that the run of the upper fracture through the weld follows the end of a length of repair weld. This repair weld can be distinguished in Figure 5 by its irregularity compared with the automatic weld aft of it. Forward of the crossing fracture, there is about an inch of automatic weld and then a further length of hand repair weld. The presence of these lengths of hand repair welding in the locality of the presumed origin of fracture arouses suspicion and they were therefore scrutinized. The back of the welds was characterized by considerable drop through of weld metal and by undercutting of more or less severity at the junction of the drop through and the parent metal. This is illustrated in Figure 6. Figure 7 is a photomicrograph of a typical section through the

edge of the weld on the other side from the fracture. Decarburization and incipient cracking of the undercut region are clearly apparent.

Thus all the circumstances support the hypothesis of fracture initiation at the weld/parent-metal junction, near the middle of the split. No known piece of evidence is inconsistent with this hypothesis. The requirement that two cracks, which were originally not connected to one another, should have started in quick succession, would indicate that at least two significant weld imperfections existed in the region. Examination of the radiographs of the repair welds suggest that there are other regions where fracture might have initiated at slightly greater stress. Unfortunately these radiographs cannot be reproduced in sufficient detail to merit their inclusion in this report.

Material taken from the ruptured tank was tested for mechanical properties and chemical analysis with the following results:

Mechanical Properties

	Yield Strength (0.2% offset) psi	Ultimate Strength psi	Elongation % in 2 inches	Hardness Rockwell C
Transverse	136,000	170,000	5	37-39
	137,000	170,000	6	
Transverse (Edges & Surfaces Smoothed)	141,700	173,000	5	37-39
	141,800	172,500	6	
Transverse (Stress Relieved 2 hours)	143,000	169,000	7	39
			7	
Longitudinal	148,400	167,000	6	
	142,800	168,000	6	
Specification Requirement	142,000 Min.	175,000 Min.	5 Min.	39 to 45

Spectrographic Analysis

Cr	Ni	Mn	Si	Cu	Ti	Mo	Al
13.18	0.21	0.37	0.42	0.07	n.d.	n.d.	n.d.

(n.d. = not detected)

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The composition is within specification, as far as was determined, except for the carbon content which is in question. Two independent laboratories reported 0.09 and 0.14% C respectively. Further determinations are being carried out.

It will be noticed that the ultimate strengths and hardnesses of all test pieces were below or on the lower limit of the specification. The yield strengths of transverse test pieces, when pulled without special preparation, were also below specification. By carefully deburring edges and smoothing the surfaces, the yield was increased on a second set of specimens to nearly the required level. This is interesting because it indicates the effect of small imperfections in reducing the nominal yield strength by acting as stress concentrators to nucleate yielding.

While the properties fail to meet the specification, the yield strengths are still considerably higher than the calculated nominal maximum stresses of 121,000 psi at failure. Thus failure in the absence of stress-concentrating imperfections is not to be expected. The low physical properties are thought, therefore, to be a contributing factor but not the prime cause of the failure. It is worth mentioning that routine material acceptance tests in the past have shown all batches received to have properties well within specification. In particular, elongation values have commonly been 7 to 10%.

Tensile tests of specimens containing transverse welded joints have been carried out at A. Co. in the past and the specimens invariably failed away from the immediate vicinity of the weld. However, it is to be expected that such weld joints were of better quality than certain regions of the tank welds, particularly the regions of repair welding. Only extensive statistical information on random sections of tank welds, taken from routine production, and without the welder's awareness of the current situation, could decide the factor of variation inherent in the welding.

A further complicating factor in this case is the heat treatment. The tankage in question was, in fact, given two full heat treatments. On the first occasion the accompanying test coupons failed to reach the required level of properties. They are reported as having a hardness of Rockwell C 37-38. Additionally the tank assembly had excessive scale on the outside (approximately 0.002" thick). On the decision of the Materials Review Board the tankage was returned to the Vendor for re-heat treatment and removal of the scale by wire brushing. On this occasion a <u>new</u> set of coupons were heat-treated with the tankage and were found to meet the specification. The first set of coupons were not re-heat-treated. It seems likely, in retrospect, that the failure of the coupons to meet specification after the first heat

treatment may have been due to non-specification material rather than faulty heat treatment; in this respect the determination of a reliable value of the carbon content is important. The second set of specimens may not have been from the same batch of material and, while qualifying the heat treatment process, did not qualify the tankage. If this situation should occur again, the original coupons should be re-heat-treated, as well as new ones. Hardness tests and microexamination for decarburization would then reveal whether the tests on the new coupons could be accepted as applying to the tankage itself.

Still another fact that should be mentioned for the sake of completeness is that the tankage was dropped accidentally, through a distance of about a foot, after final heat treatment. After pressure testing and dye checking it was then accepted as being usable. Whether or not this is significant cannot be decided with certainty. However, it would seem to be of incidental interest only. Certainly the imperfect welding alone is sufficient to account for the failure at the high level of stress involved, even if all the other factors were favorable.

An unresolved question is why the tank did not fail on the proof test at 550 psig (which followed the dropping of the tank) and yet did fail at Fort Churchill at 520 psig. There are several possible explanations - unfortunately none of them is capable of verification. One is a possible error in reading or calibration of a pressure gage. Both parties are confident of the accuracy of their gages and the reliability of the readings taken. A second possibility is that the temperature of the tank then tested at Fort Churchill may have been significantly lower than when it was tested in California. However, no regions of "brittle" fracture were found. The third possibility is that the case in question is a rare example of high-strain fatigue involving only two cycles. To put this in another way, while the duration of the first pressure test was too short for the development of a complete failure, it was nevertheless sufficient for some localized damage to occur at weld-edge imperfections, which then permitted fracture initiation at a lower stress on the second pressurization. This is admittedly speculative, yet there have been cases of failures to gas pipe lines which occurred on loading up to a working stress lower than the proof stress to which they had been previously tested. Seemingly there might be a connection between these and the present failure.

However the matter is regarded, attention focuses back to the imperfections associated with the welds. Although a complete explanation of the failure has not been reached because of the lack of data, the most likely means of significantly decreasing the probability of failure in the future is to improve the quality of the welds. Any other measures which might be taken would result in reduced performance of the rocket. Remedial action is further discussed in a later section of this report.

Failure of Aerobee - Hi NRL #45 Helium Pressurizing Tank while ready for Launching at Fort Churchill

The helium tank of the second Aerobee - Hi rocket scheduled to be launched from Fort Churchill burst suddenly about 15 minutes before the intended time of launching. The circumstances of this failure, as far as can be ascertained, are as follows:

The tankage had been pressure tested by A. Co. prior to shipment as outlined in Appendix I. Further pressure tests had been satisfactorily completed at Fort Churchill. Up till then no acid had been introduced into the oxidizer tank. In preparation for launching, the oxidizer tank was filled with red fuming nitric acid. In the vertical position, with the helium tank at the top, there is a small space in the acid tank above the level of the acid. However, the bottom of the helium tank, which is also the top of the acid tank, dips into the acid. The launching was delayed for various reasons and consequently the acid tank remained filled with acid for a total of 22 hours. This was separated into two periods, the tank being emptied and neutralized once and later refilled. Of this period the helium tank was pressurized three times, taking about 45 minutes each time to reach full pressure, and at full pressure (nominally 3750 psig) for a total of 2 hours. In all, therefore, the helium tank was under some stress while in contact with the acid for a total of about 4 hours. The final pressurizing was complete 37 minutes before the failure occurred. The gage then read 3750 psig. It dropped gradually to 3675 psig during the 37 minutes. It is understood that this was due to cooling of the helium to ambient temperature after having been heated during pressurizing of the tank. Ambient temperature in the vicinity of the tank is believed to have been about 90°F.

The failure was violent, the whole helium tank, together with the instrumentation section on top of it, being neatly separated from the oxidizer tank, while at the same time the lower hemispherical dome of the helium tank separated into five pieces which were projected violently away from the rocket. Two of them were found embedded in the walls of the building. Figures 8 to 11 illustrate the features of the damage.

Although the recovered pieces of the dome were too badly distorted to be fitted together for photographing, it was nevertheless possible to match the fracture surfaces. An attempt has been made in Figure 12 to sketch schematically the principal fractures in the form of an end-on view of the tank. While this sketch is not accurate in detail it is considered to be accurate in the important features. It will be noticed that one of the five pieces which separated was not recovered.

Part of the dome did not separate from the helium tank. In Figure 12 this is located along the arc CDEF, reference to Figures 9, 10 and 11 will help visualization. At D the fracture surface is several inches from the rim of the dome. From D it runs down on either side to the weld joining

the helium tank to the oxidizer tank and follows this weld in both directions to the points C and F. At these points it crosses to the weld joining the dome to the body of the helium tank and follows this weld along the arc CBAF. Near A is a noticeable discontinuity where a fracture running from C towards F might have met one running from F towards C. All of this fracture surface is of the oblique shear type. These features can also be seen in Figure 13 which is a close-up view of this fracture surface.

Between A and B there is a noticeable shear lip on the <u>outside</u> of the fracture whereas there is a shear lip on the inside of the fracture diametrically opposite. Furthermore, in the vicinity of A to B, the outside of the body is noticeably concave in the longitudinal direction, whereas it has no noticeable curvature in that direction elsewhere. These features indicate that when the helium tank was separating from the oxidizer tank the top of the helium tank was deflected approximately in the direction A. For this to happen, separation must have occurred first somewhere approximately opposite A. There is another good reason for supposing that separation was completed near A, or at least, somewhere between C and F. If fracture had started there, the helium would have escaped to the atmosphere and while the body of the tank might have separated completely, there would be no tendency for the lower dome to be projected out of the oxidizer tank. The pressure exerted by the helium would, in this case, have tended to push the dome <u>into</u> the oxidizer tank. To explain the fact that the pieces of the dome were projected violently outwards, it is necessary to suppose another sequence of fracture.

A reasonable sequence would be that fracture initiated in the dome, allowing the helium to enter the oxidizer tank. Because of the very small air space in the oxidizer tank the resulting pressure would be not much less than the 3675 psig in the helium tank - much more than the oxidizer tank was intended to sustain. The two tanks would therefore separate immediately around the tank to tank weld, projecting the helium tank upwards. Meanwhile the fracture in the dome of the helium tank would continue to propagate from the force of the out-rushing helium. Thus the helium tank might have been projected upwards as a whole while the dome was still fracturing, so that final separation of the five pieces of the dome occurred in mid-air, projecting them in several directions.

If this sequence is correct, it might be possible to find evidence of fracture initiation in the pieces from the dome. Such evidence was indeed found. By far the greater part of the fracture surfaces of these pieces was of the oblique shear type; however, in the region designated "brittle fracture region" in Figure 12 there were easily distinguishable sections of a different type of fracture. One of these sections is illustrated in Figure 14. These occurred on pieces AF and ED only, and the corresponding surfaces could be matched on these two pieces. These fracture surfaces

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were characterized by granular fracture normal to the convex surface (i.e., the surface in contact with the acid), continuing part way through the section, and completed by the usual shear fracture to the inner concave surface. These features are clearly shown in Figure 14.

In view of the various circumstances: (1) sudden fracture under constant stress after sustaining the stress for some time, (2) contact with acid under stress, (3) short sections of granular fracture normal to the surface surrounded by oblique shear fracture, the most likely cause of initiation of fracture is stress-corrosion cracking. Microscopic examination confirmed the presence of typical intergranular stress corrosion cracks in the vicinity of the granular fractures. Such a crack is shown in Figure 15 which is a photomicrograph taken from a microsection normal to the dome of the tank near an area of granular fracture. Such cracks were found frequently on the convex surface, which had been in contact with the acid, in each of several microspecimens examined. No cracks were found on the concave surface which had not been in contact with the acid.

The evidence is therefore completely in accordance with the hypothesis of initiation of the failure by stress-corrosion cracking. A. Co. Materials Engineers have stated their concurrence in this diagnosis.

Discussion of the Aerobee - Hi Failures

Prior to the two failures just described, four NRL Aerobee - Hi rockets had been flight tested at White Sands and a number of other Aerobee's had successfully passed proof tests without failure. The following Table, provided by A. Co., lists the tankages manufactured to date.

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HISTORY OF 410 SS TANKS FOR MODEL AJ11-6

AND AGVL-0113 AND AGVL-0114 AEROBEE ROCKETS

(Gas Bottle and Propellant Tanks proofed at Fabrication - Aerojet Witness)

(Propellant Tanks Proofed at Aerojet)

TANK SERIAL NO.	AEROBEE MODEL	ROCKET SERIAL NO.	AEROJET PROOF TEST	STATIC FIRE TESTED	FLIGHT TESTED	REMARKS
1.	AJ11-6	GM54-1601	Yes	Yes	Yes	HADC
2.	"	GM54-1602	Yes	No	Yes	HADC
3.	"	Spare	Yes	No	No	
4.	"	AF-3	Yes	Yes	Yes	HADC
5.	"	AF-4	Yes	Yes	No	
6.	"	AF-5	Yes	No	No	
1.	AGVL-0113	NRL-39	Yes	Yes	Yes	WSPG
2.	AGVL-0113	NRL-42	Yes	Yes	Yes	WSPG
3.	AGVL-0113	NRL-46	Yes	Yes	Yes	WSPG
4.	"	NRL-50	Yes	Yes	Yes	WSPG
5.	"	NRL-45	Yes	No	No	Ft. Churchill - Gas bottle failed at approx 3600 psig
6.	"	NRL-48	Yes	No	No	Ft. Churchill Oxid. Tank split at weld at approx 520 psig.
7.	"	NRL-47	Yes	No	No	
8.	AGVL-0113	NRL-43	Yes	No	No	
9.	AGVL-0114	NRL-40	No	No	No	
10.	AGVL-0114	NRL-41	No	No	No	
11.	AGVL-0114	NRL-44	No	No	No	
1.	AJ11-6	AF-7	Yes	No	No	
2.	AJ11-6	AF-8	Yes	No	No	
3.	AJ11-6	AF-9	No	No	No	
4.	AJ11-6	AF-10	No	No	No	
5.	AJ11-6	AF-11	No	No	No	Oxid. Tank split at weld; Made new tank welds passed X-ray.
6.	AJ11-6	AF-12	No	No	No	
7.	AJ11-6	AF-13	No	No	No	
8.	AJ11-6	AF-14	No	No	No	
9.	AJ11-6	AF-15	No	No	No	

In particular, NRL #50 had a notably successful flight. As a consequence of the oxidizer tank failure of NRL #48, a review was made of the radiographs of the longitudinal seam welds of these two tankages (other tankages were reviewed as noted later). The results of this review were inconclusive. On the whole the welds of NRL #50 appeared to be no better than those of NRL #48. Both tankages contained a number of hand repairs and the interpretation of radiographs is not a sufficiently precise art for it to be possible to say that no region in the NRL #50 welds was as bad as the particular section of NRL #48, weld L4 at which failure is believed to have initiated. At present insufficient data is available to be able to say what is, and what is not, a critical weld defect, on a part where the stresses may reach 90% of the 0.2% offset yield strength. Proof testing of the tankages is, of course, intended to be a further and more severe test of the weld joints, as well as of other features of the tankages. However, the present case, in which failure at a weld occurred during a second proof test, after the tankage had successfully passed the first proof test, indicates that even proof testing above the expected stress levels is no certain guarantee of future performance. By increasing the period of holding at proof pressure from the 2 minutes now required by the specification to 30 minutes, or more, the value of the test could be increased.

Unfortunately, there would appear to be no other testing procedure which could be applied to prove the tankages with a higher degree of confidence. However, there are two other methods of reducing the likelihood of this type of failure*. The first, use of a larger factor of safety, carries too large a weight penalty to be feasible for the intended application of the tankages. The second is a general improvement in quality of welding which is believed to be possible and which can be effected by increasing the stringency of weld inspection and further restricting the conditions under which repair welding is allowed and accepted. While this cannot eliminate the possibility of a significant defect occurring in a tank which passes inspection, it can reduce the likelihood considerably.

This is, in fact, what A. Co. propose to do. While the previous specification allowed hand repair welds at the discretion of the inspector examining the radiographs, such repairs will now be allowed only on the action of the Material Review Board consisting of two representatives from A. Co. and a Bureau of Aeronautics representative. This will certainly result in more rejections of tankages in process, and ultimately in improved quality of welding. In view of the seriousness with which the failure is regarded at A. Co. it is also likely that everyone concerned will regard the welds with more suspicion than hitherto.

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* In addition to the step already taken, at Fort Churchill, of reducing the Helium tank operating pressure from 3750 to 3400 psig.

It is difficult to see what further action could be taken at this time, other than the increase in holding time during proof testing, without causing very serious delays in the scheduled deliveries of rockets. Undoubtedly as more experience is gained in the design and testing of these highly stressed pressure vessels it will be possible to produce them with a higher degree of confidence that premature failures will not occur. In a sense, the important decision to be made is whether to gain the necessary experience by an expensive and time consuming test program on the ground or, at somewhat more risk, to gain it while at the same time going ahead with the launchings.

At this point it is perhaps appropriate to mention that the three rockets NRL #43, #47, and #40 which are at, or enroute to*, Fort Churchill were also reviewed in respect of weld radiographs and inspection histories. The reviews were inconclusive in the sense that the rockets could not be said to be either better or worse than NRL #48 and #50.

Turning now to the stress-corrosion cracking failure of NRL #45, it is considered that this is not due to exceptional circumstances so that the risk of further failure cannot be eliminated merely by changing procedures of preparing for firing. It is apparently true that this particular tank was under stress in contact with acid longer than any previous tank had been. However, the qualities required in the rocket include the ability to be held ready for firing for a reasonable period until a number of different circumstances are favorable. The holding period of this rocket (22 hours charged with acid including about 4 hours with the helium tank pressurized) can not be regarded as excessive. It is therefore necessary that positive steps be taken to preclude the risk of stress-corrosion cracking failure within the contemplated maximum delay period.

Fortunately it appears likely that something can be done in this respect. However, insufficient data is available at present and stress-corrosion testing has to be carried out to obtain the necessary data. This is currently being done at A. Co. Preliminary results indicate that by the use of inhibited acid, rather than raw acid, the life under a given stress before the part finally fails by stress-corrosion cracking can be increased many times - perhaps indefinitely. There is, however, a question of whether the inhibitor will reduce the performance of the rocket significantly. This has yet to be resolved. At present inhibition seems to be the most promising prospect. Failing this, the question of a suitable protective coating within the tank is worth consideration. The problems in developing a reliable coating appear to be more extensive than those associated with the use of an inhibitor. There are also less likely possibilities which would require even more time to investigate and can be neglected for the purpose of the present report.

Further discussion of stress-corrosion cracking and prevention (or mitigation) will now be deferred until the consideration of the relationship of these failures to the Vanguard program since data compiled to date

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* Since this report was written, it is understood that #47 and #43 have been successfully launched.

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has been concerned with the conditions prevailing in the Vanguard rather than the Aerobee - Hi. It is expected that a more complete report of the work on this subject at A. Co. will be issued by that Company when sufficient data has been compiled.

In summary, the reasons for the two Aerobee - Hi Tankage failures are understood, and action has been, and is being, taken by A. Co. to reduce the likelihood of further failures.

Construction, Manufacture and Testing of the Vanguard Tankage

A schematic drawing of the Vanguard Tankage is shown in Figure 16. Details of welds joining the formed ends to the fuel and oxidizer tank bodies are shown in Figure 17 because such a weld was involved in the failure of one Vanguard tank during proof testing.

In this tankage the helium pressure vessel is a sphere with the weld joining the two hemispheres parallel to the axis of the rocket. The fuel and oxidizer tanks are closed at one end of each by this sphere, along a circumference perpendicular to the closure weld of the sphere, i.e., normal to the axis of the rocket. Assembly is carried out by slipping the ends of the two tanks over the sphere and making a circumferential fillet weld of each tank to the sphere.

The material used is the same as that for the Aerobee - Hi, viz., type 410 stainless sheet steel, and the welding method, Argon arc, is also the same. Heat treatment is carried out in the same furnace using an endothermic atmosphere outside and argon inside the tankage. Heat treatment procedure is different in the following respects:

	Aerobee - Hi	Vanguard
Austenitizing	1800°F - 1/2 hour and Air cooled	1700°F - 1 hour and Air cooled
Subzero	None	-100°F - 8 hours
Tempering	600°F - 3 hours	825°F - 2 hours
Hardness Req'd	Rc 39-45	Rc 39-42
Min. Yield Strength (0.2% offset)	142,000 psi	147,000 psi
Min. Elongation in 2"	5%	7%

The superior tensile properties for the Vanguard heat treatment have been substantiated on 11 lots of material, including three different thicknesses, by A. Co. The properties obtained in tensile tests of welded and not-welded test pieces are shown in Figure 18 for six different combinations of heat

treatment variables. The code at the bottom of each column of points in Figure 18 indicates austenitizing temperature, cold treatment and tempering temperature. Examination of this data indicates that little or none of the improvement is associated with the subzero treatment, whereas the effect of the lower austenitizing temperature and the higher tempering temperature both contribute to improve the yield strength. Ductility does not appear to depend strongly on the heat treatment variables, although there does appear to be an average improvement in Elongation of 1% between Aerobee and Vanguard.

Hydrostatic proof testing of the assembled and heat-treated tankage consists of (1) applying 398 ± 10 psig to all three tanks for 2 minutes, (2) reducing pressure to 298 ± 10 psig and testing for leaks in the propellant tanks, (3) applying 315 ± 10 psig to all three tanks and then increasing the pressure in the helium tank to 1900 ± 30 psig for two minutes. The pressure in the helium tank must be reduced to 1585 psig before the pressure in the propellant tanks is reduced.

The following major stresses are understood to correspond to the various pressures:

Pressures and Stresses in Vanguard

	Helium Tank		Propellant Tanks	
	Pressure psig	Stress psi	Pressure psig	Stress psi
Minimum Yield	-	147,000	-	147,000
Proof Test	(1900-315) = 1585	141,000	408	130,000 (body) 139,000 (head)
Operating	(1700-340) = 1360	122,000	340	110,000 (body) 116,000 (head)

Following satisfactory proof testing, and some further assembly operations, the whole Vanguard unit is charged with fuel, acid and helium so that static firing tests can be conducted in order to adjust the operation of the motor. These static firings involve operations of the tanks under full working pressures. The complete test schedule will vary with circumstances but it is believed that the tankage may be under pressure in contact with acid, etc., for at least 10 hours. After the firing tests, the tanks are drained, neutralized and dried for shipment.

Summary of Known Circumstances of Three Vanguard Tankage Failures

Three failures of Vanguard tankages are known to have occurred. Full details are not available but it is known that each failure was due to circumstances which will not recur intentionally. It is therefore sufficient to give only a brief summary of each.

The first failure was a fracture of a helium sphere which originated at the boss shown in Figure 16. This boss is normally a type 410 stainless steel forging. In the case under consideration, a type 431 stainless steel boss, machined from bar stock, had been substituted because of procurement difficulties (the tank was intended only for test purposes). This boss did not have the structure or grain flow necessary to sustain the stresses and therefore split into four pieces at 1565 psig during pressure testing. These fractures propagated into the helium sphere a short distance and then terminated. Recurrence of this type of failure is not to be expected since no further spheres will be fitted with type 431 bosses. Subsequent proof testing of other spheres has demonstrated the ability of type 410 bosses to sustain the stresses (which are lower than in the actual tankage).

The second failure occurred to the fuel tank of a unit having a head to body weld of the original type shown in Figure 17. The head blew off at 390 psig, the fracture running between the two welds shown in the Figure, joining head to body and skirt to head, sometimes along the edge of one weld and sometimes along the edge of the other. It was thought to be a weld-associated failure and, as a consequence, the joint design was changed. The first modification was to bring the two welds closer together and then fuse them with a third bead. The current modification consists of tack welding and then joining the three pieces with one heavier, double fillet weld as indicated in Figure 17. This joint is considered to be much more reliable than the original and, providing proper control is exercised over the welding, should not be a particular source of future trouble.

The third failure occurred recently during a proof test following an interrupted firing test. This was a brittle failure of the conical end of the oxidizer tank. On examination, the failed part was found to have a hardness of Rc 52-53 compared with Rc 41-43 for the rest of the tankage. Subsequent investigation traced this exceptional hardness to improper process annealing between forming operations. Although the specified atmosphere was used, (dry argon, isothermal cycle: 1600°F - 1/2 hour followed by 1350°F - 5 hours), the heads had been separated by newspapers to prevent abrasion ! This evidently resulted in very effective carburizing of the heads. The most surprising thing is that out of 25 heads so treated, only 19 of them cracked during the remaining forming operations and the others somehow got through to be incorporated into complete tankages. It is understood that the other 5 heads have been located and scrapped. Also the sub-contractor now forming and annealing the heads is not the same as the one at which the defective heads were produced. Additionally, A. Co. now has a Metallurgist as an observer at the current sub-contractor's plant.

Recommendations

In view of the similarities in material, construction and operating conditions of the two rockets, failures due to either weld imperfections or stress corrosion could occur to either Aerobee - Hi or Vanguard rockets in the future. The following recommendations are intended, therefore, to apply to both:

1. The most urgent requirement is a comprehensive stress-corrosion test program which will provide adequate design information and cover the following variables:

(a) The effect of biaxial as compared with uniaxial tensile stress.
(b) The effect of stress level.
(c) The effect of temperature.
(d) The effect of the condition of the steel (heat treatment).
(e) The effect of weld joints and other "natural" stress raisers.
(f) The effect of acid composition (white vs red).

Also the following remedial measures should be investigated consecutively, in the order given, or simultaneously:

(a) Inhibitors.
(b) Surface treatments of the tank interior.
(c) Coating of the tank interior.

The program currently being carried out by A. Co. seems to meet most of these requirements. After that Company has had an opportunity to report their initial results and outline their further program, consideration can be given to additional testing at A. Co. or elsewhere.

Present indications are that inhibition with 1/2 - 3/4% hydrogen fluoride (anhydrous) shows great promise. If this idea can be worked out satisfactorily, there may be no pressing need to complete the whole program of stress-corrosion testing.

2. Welding procedures and inspection of welds can be improved. Measures now being taken by A. Co. for the Aerobee - Hi rocket seem to be as adequate as possible without incurring serious delays. The one additional recommendation that can be made is to increase the holding time during hydrostatic proof testing from 2 minutes to at least 30 minutes. This would increase the opportunity for any incipient defect to propagate during the proof test. Unfortunately, more effective inspection and proving methods than those now being used do not exist, although the application of these current methods, and perhaps of other methods, will become more effective as the necessary basic experience is gained in design, testing and operation of these highly stressed structures. All knowledge rests ultimately on experience, and without failures, either accidental, or intentional by testing to failure of the part itself or of a specimen representative of some aspect of it, there can be no basis for prediction.

3. It would be inappropriate here to make definite recommendations regarding the procedures for preparing to launch the rockets. However, it will be clear that it is desirable at all times to minimize the duration of exposure of the steel to acid while under stress. Also, it is undesirable to load and unload the structure repeatedly, whether in contact with the acid or not. Not much is known about the effects of repeated stress close to the yield point, but there are reasons for supposing that serious, accumulative damage might occur with each cycle, especially in the vicinity of notches or other stress concentrators and modifiers of the stress system. The fact that one, or even several, tankages might survive stress cycling tests, although an

excellent indication, is no guarantee that every tankage would survive. The decision which has already been made, to operate with a pressure of 3400 psig in the Helium tank instead of 3750 psig will clearly tend to reduce the risk of failure and is desirable so long as performance is not adversely affected beyond what can be tolerated.

APPENDIX I

OUTLINE OF NAVY AEROBEE - HI 410 TANK ASSEMBLY

I. DESIGN CRITERIA

A. PRESSURE TANK

(1) Cylinder wall thickness is .207 inches minimum.
(2) Head wall thickness is .105 inches minimum.
(3) Proof pressure is 4000 psig (Stress of 142,000 psi).
(4) Rupture pressure is 4900 psig (Stress of 175,000 psi).
(5) Operating pressure is 3750 psig (Stress of 132,000 psi).

B. PROPELLANT TANK

(1) Cylinder wall thickness is .032 inches minimum.
(2) Head wall thickness is .045 inches minimum.
(3) Proof pressure is 550 psig (Stress of 129,000 psi).
(4) Rupture pressure is 750 psig (Stress of 17,500 psi).
(5) Operating pressure is 450 psig (Stress of 105,000 psi).

II. MATERIAL PROCUREMENT (Specification AMS-M58)

A. SHEET STOCK CHEMICAL COMPOSITION

(1) Stock must conform to QQ-S-766.
(2) Stock must conform to AMS-5504C.
(3) Carbon range is .115 to .150%.
(4) Silicon is limited to .50% maximum.
(5) Aluminum is limited to .05% maximum.
(6) Chromium range is 11.00 - 13.50%.

B. SHEET STOCK HEAT TREAT SPECIMENS

(1) Two specimens for each heat.
(2) Perpendicular to the rolling direction.
(3) 175,000 psi minimum ultimate tensile strength.
(4) 142,000 psi minimum yield tensile strength.
(5) Hardness is 39 to 45 on Rockwell C scale.
(6) Elongation in 2 inches is 5% minimum.

C. PACKAGING OF SHEET STOCK

(1) Each sheet separated by paper to prevent scratching.
(2) Stock packed in wooden boxes.

D. WELDING ROD

(1) Type 410 bare rod (wire) per QQ-S-763).
(2) Carbon range is .115 to .150%

TANK ASSEMBLY PROCEDURE (Specification AES-A2821.6)

A. Radiographic inspection required on all stressed 410 welding.

B. Dye penetrant inspection required on all welds.

C. Stress Relieve (1200°F - 2 hours) after welding each component.

D. Clean tank with carbon tetrachloride before heat treatment.

WELDING (Specification AES-W2821.4)

A. Preheat 350°F - 450°F.

B. Postheat 350°F - 450°F for 5 minutes.

C. Stress relieve at 1200°F for 2 hours.

D. Radiographic Inspection.

(1) Propagating defects not permitted.
(2) Slag inclusions not permitted.
(3) Tungsten inclusions over 1/5 of thinnest section being welded not permitted.
(4) Tungsten inclusions (T/5 or less) shall be separated by one inch and no more than 6 in any 12 inches of welding.
(5) Porosity over 1/5 of the thinnest section being welded not permitted.
(6) Porosity (T/5 or less) shall be separated by 1/2 in. and no more than 6 in any 12 inches of welding.
(7) Linear defects not permitted.
(8) Undercutting not permitted.
(9) Material thinning not permitted.

E. Repair welding more than three times not permitted. Fourth time at MRB.

F. Repair welding more than 20% of effected weld not permitted.

HEAT TREATMENT (Specification AES-H2821.5)

A. FURNACE

(1) Non-oxidizing atmosphere.
(2) Atmosphere dew point 50 - 60°F.
(3) Argon flow through tanks while in furnace for hardening.
(4) Tank is suspended in vertical position.

B. HARDENING PROCEDURE

(1) Initial furnace temperature is 1450°F to 1500°F.
(2) Heat tank at 1800°F for 30 minutes.
(3) Cool in still air.

C. TEMPERING PROCEDURE

(1) Heat tank at 600°F for 3 hours.
(2) No protective atmosphere required.
(3) Cool in still air.

D. INSPECTION

(1) Hardness of Rockwell C 39 to 45 obtained.
(2) Furnace charts of times and temperatures involved.

E. SURVEILLANCE

(1) Metallurgist and Engineer from project witnessed complete heat treatment of first ten tanks.

VI. PRESSURE TESTING (Specification ATP-LA-9T.003)

A. PREHEAT TREATMENT TESTING

(1) Testing performed after stress-relieving.
(2) Pressure tank proof tested at 550 psig for 2 minutes, then reduced to 400 psig checked for leakage.
(3) Propellant tank proof tested at 70 psig for 2 minutes then reduced to 35 psig and checked for leakage.
(4) Proof pressures correspond to 15,000 psi stress.

B. POSTHEAT TREATMENT TESTING

(1) Pressure tank proof tested at 4000 psig for 2 minutes then reduced to 2000 psig and checked for leakage (sub-contractor only).

(2) Propellant tanks proof tested at 550 psig for 2 minutes then reduced to 400 psig and checked for leaks (sub-contractor and AGC).
(3) Tanks measured before and after proof testing.

C. GAS LEAKAGE TESTS (Sub-contractor and AGC).

(1) Pressure tank tested at 200 psig.
(2) Propellant tanks tested at 100 psig.

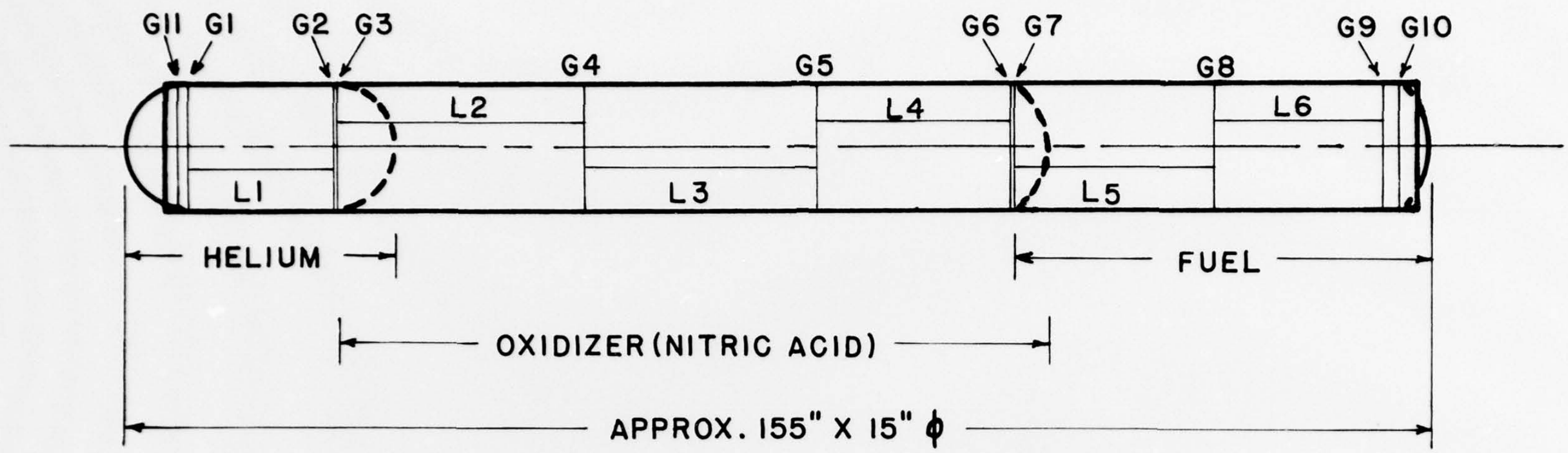

Figure 1 - Schematic Drawing of Aerobee - Hi Tank Assembly Showing Locations of Principal Welds

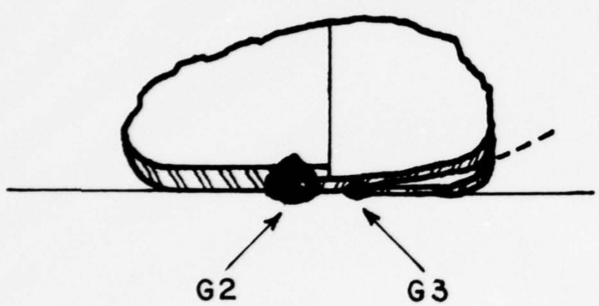

Figure 2 - Detail of Weld G2 and G3

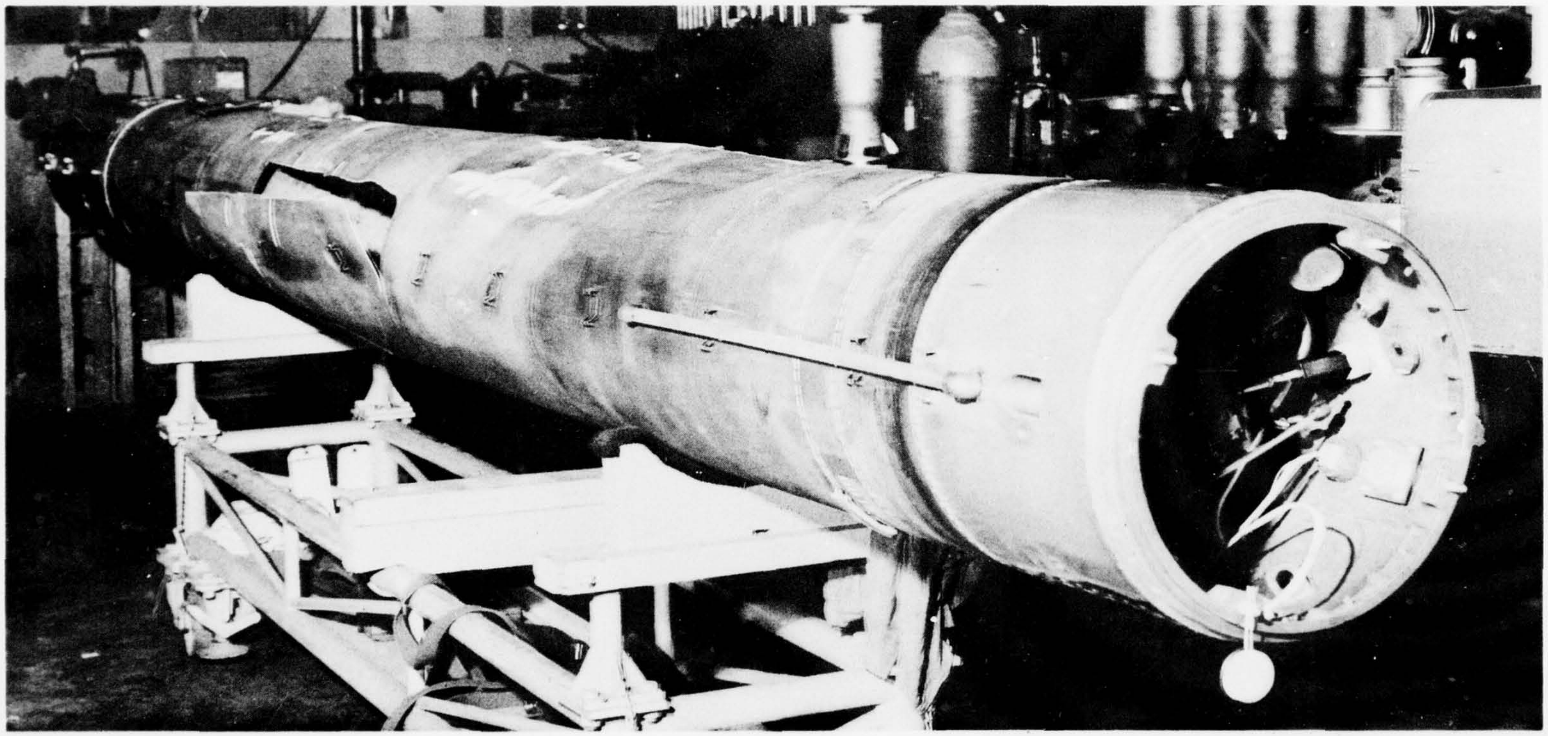

Figure 3 - View of Aerobee - Hi NRL #48 from forward end showing burst oxidizer tank

Figure 5 - Close-up view of Central Section of Fracture in Oxidizer Tank of NRL #48

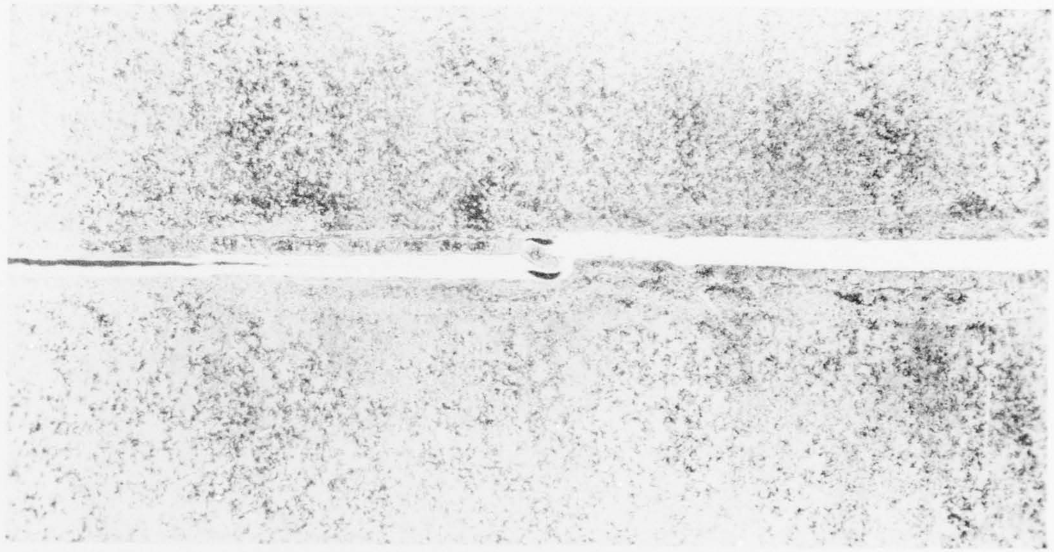

Figure 6 - View of Back of Central part of the Fracture in the Oxidizer Tank of NRL #48

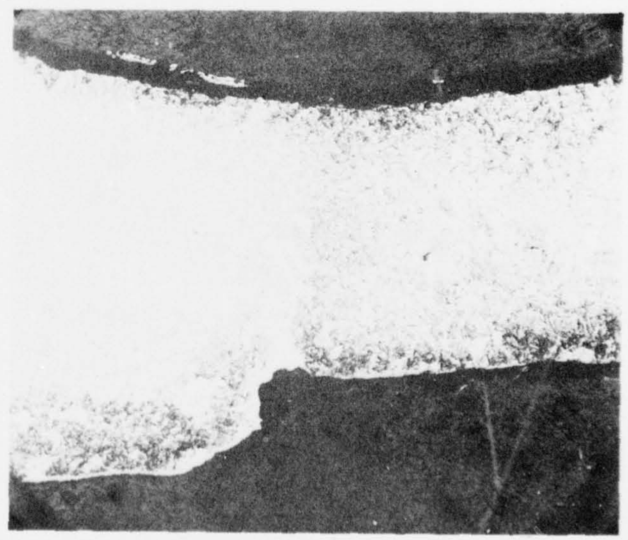

Figure 7 - Photomicrograph of Section through Edge of Weld on the other side from the Fracture. This is a Hand Repair Weld and shows Drop-through at the Back (bottom of photo), Undercutting and Decarburization. (40 X, Approx) Etched Nital.

Figure 8 - View of Top of Oxidizer Tank of NRL #45 after separation of Helium Tank

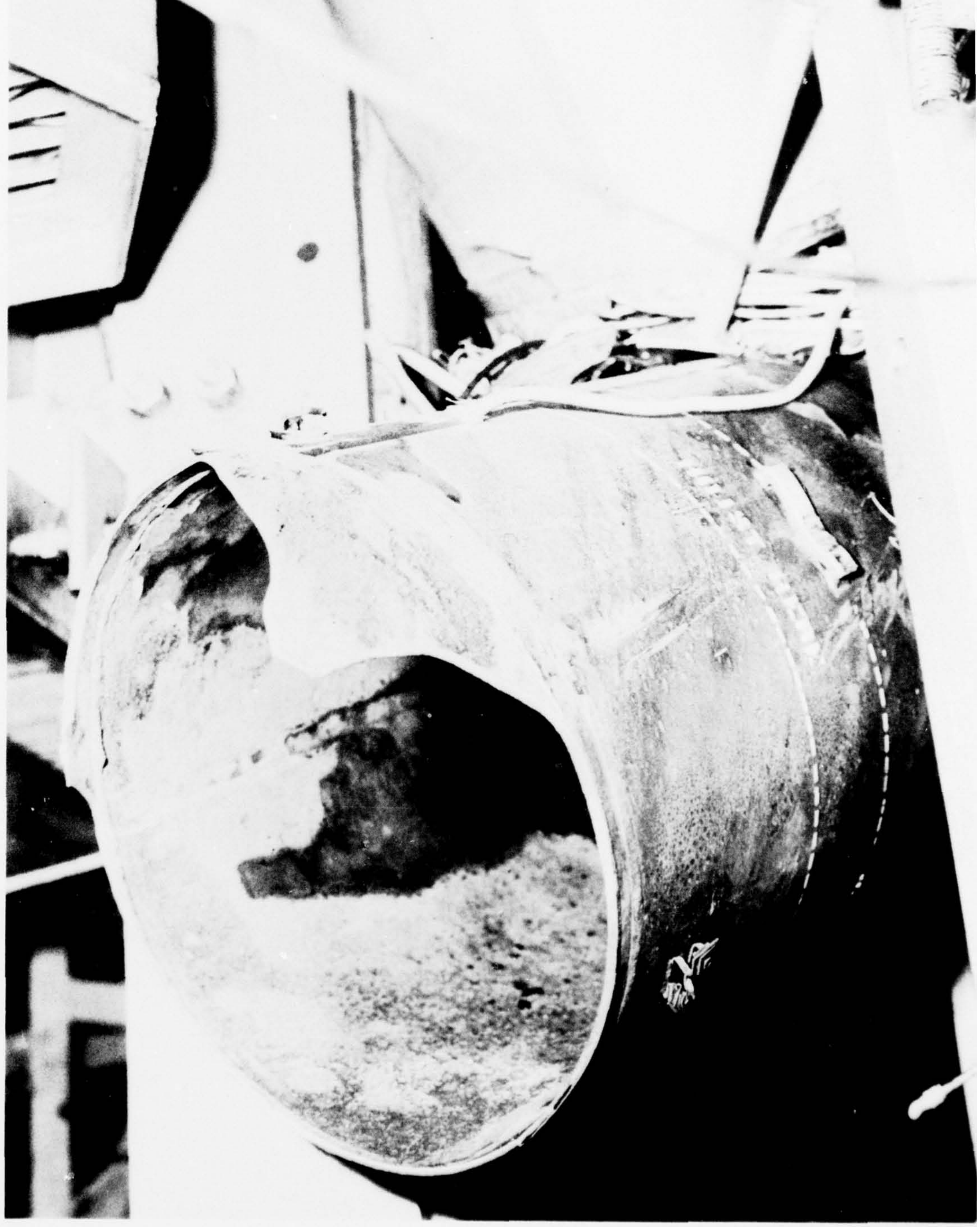

Figure 9 - View of fractured end of Helium Tank in position in which it was found after Failure of NRL #45

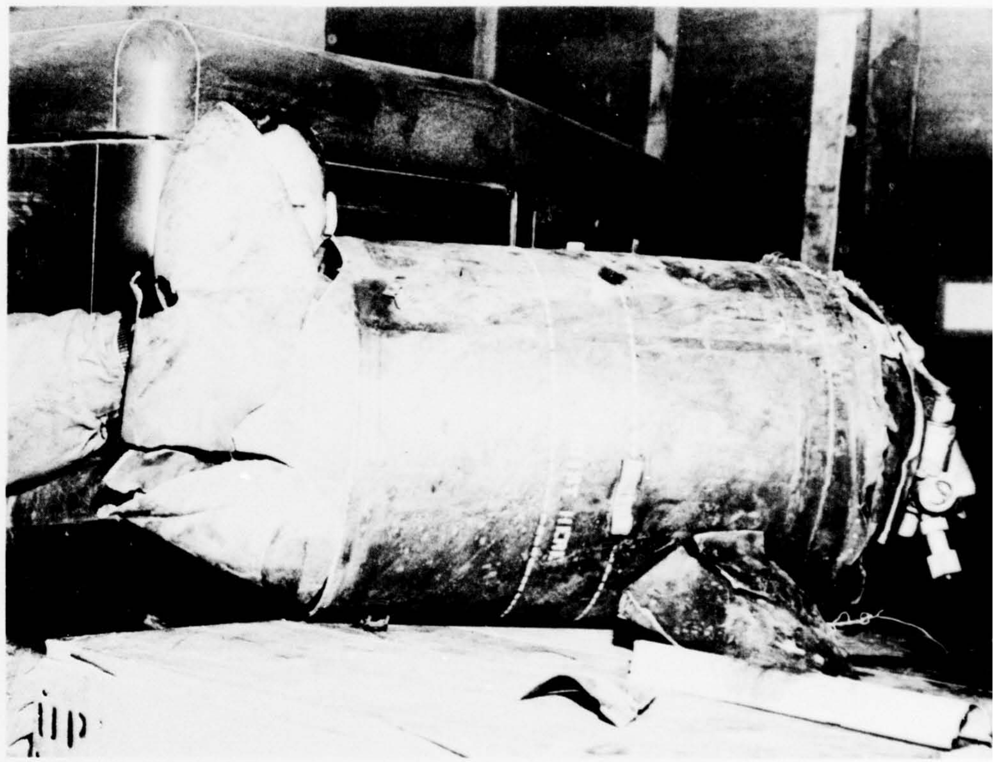

Figure 10 - View of Helium Tank of NRL #45 after removal from Launching Structure showing two separated pieces being held in position and two other pieces in foreground

Figure 11 - Another view of the Fractured End of the Helium Tank with two of the separated pieces

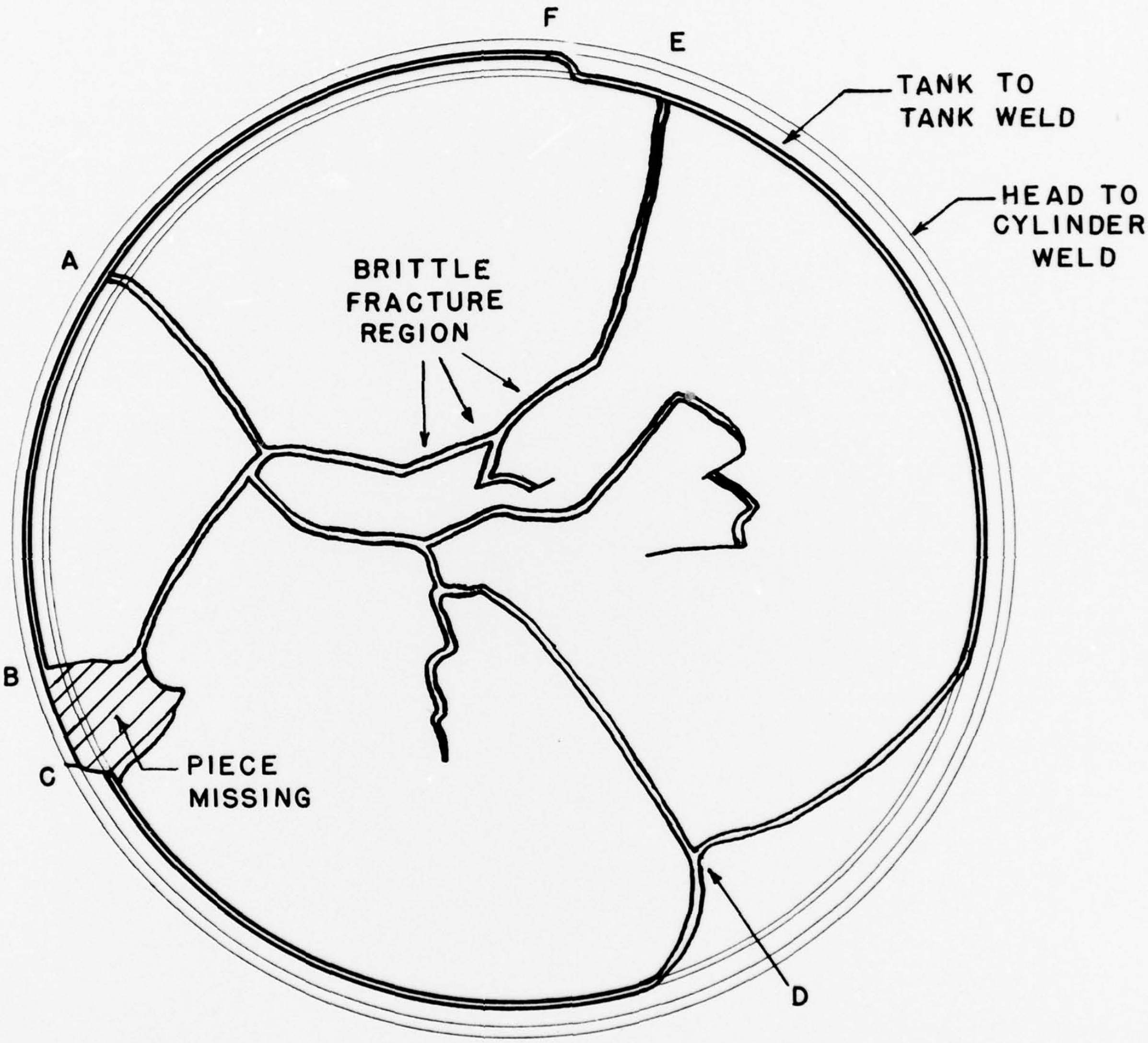

Figure 12 - Schematic Reconstruction of Fractured Hemispherical Dome of Aerobee - Hi Helium Tank

Figure 13 - Close-up view of fractured surface of Helium Tank

Figure 14 - Section of NRL #45 Dome Fracture showing Stress Corrosion Fracture on the acid side (bottom) and Shear Fracture on the Helium Side (top). 2X (Approx)

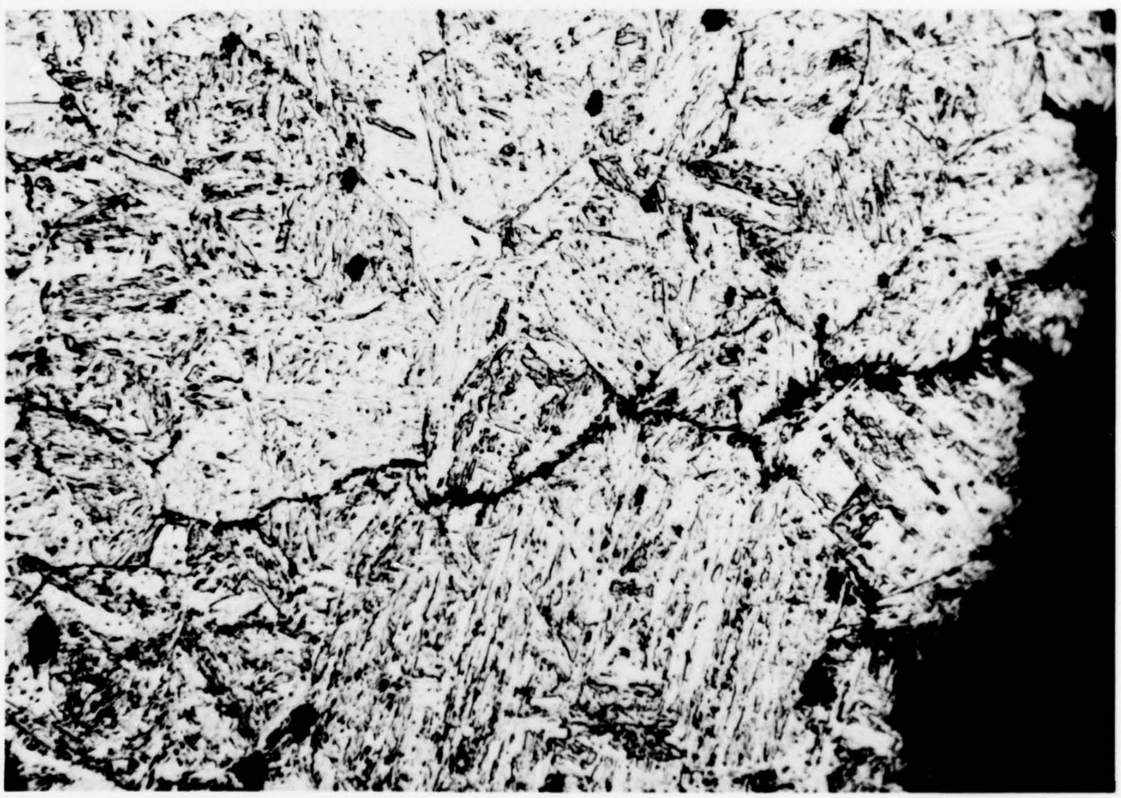

Figure 15 - Photomicrograph of stress corrosion crack in the vicinity of the Fracture shown in Figure 14. 1000 X, Etched Picral/HCl

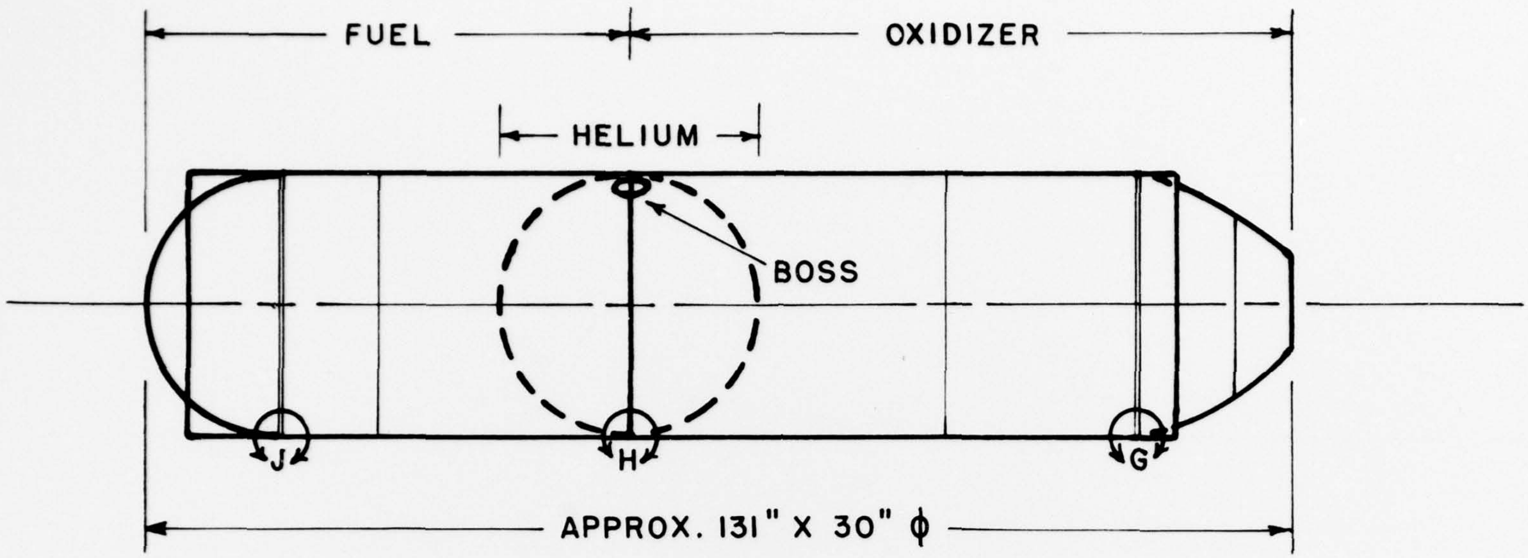

Figure 16 - Schematic of Vanguard Tank Assembly Showing Locations of Girth Welds only

Figure 17 - Detail of Weld J (G is Similar) as Originally Designed and as Now Designed

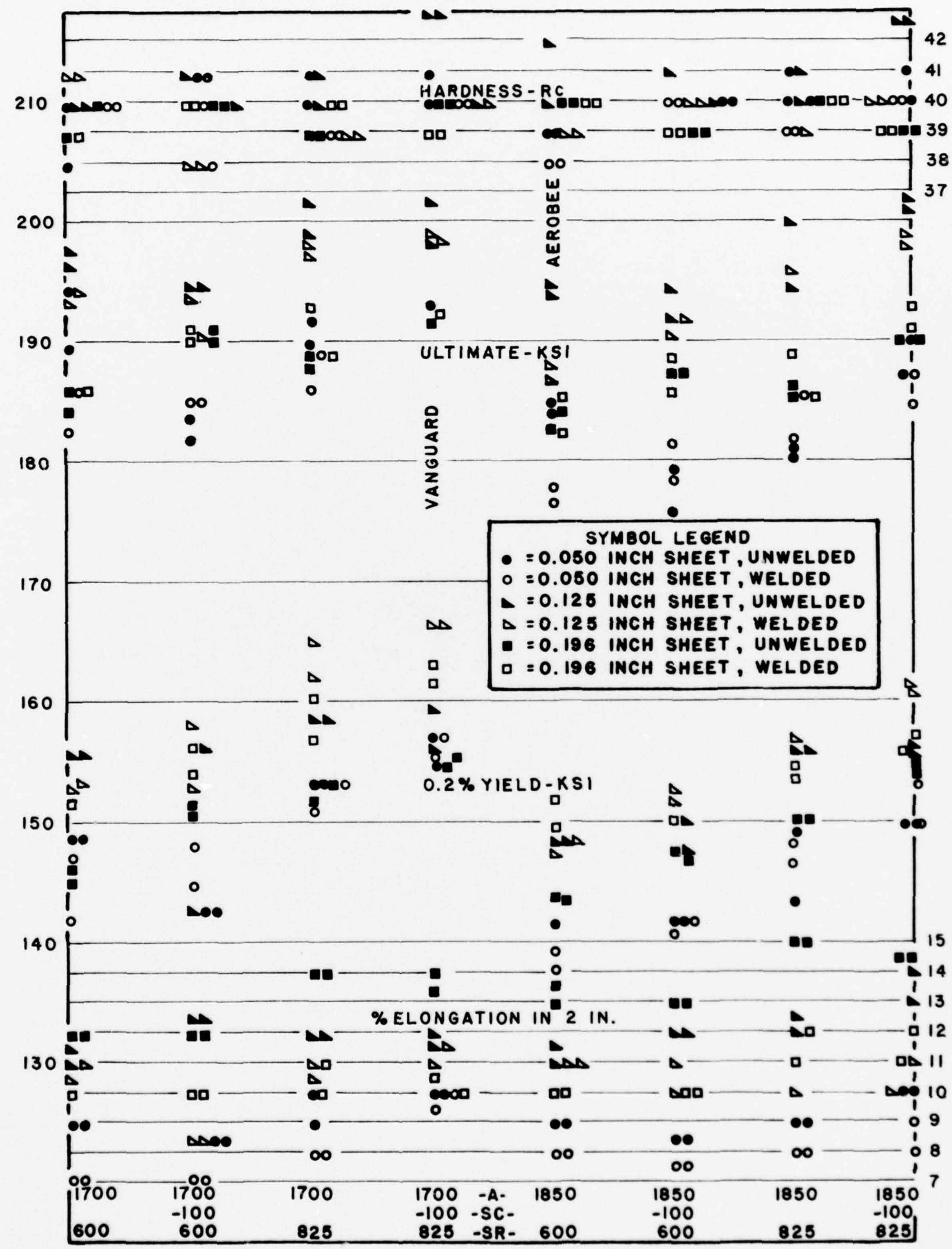

Figure 18 - Heat Treatment Condition vs Properties Type 410